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TROPOSPHERIC EFFECTS ON MILLIMETER WAVE PROPAGATION.(U)

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**Final Technical Report**  
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# **TROPOSPHERIC EFFECTS ON MILLIMETER WAVE PROPAGATION**

**University of Washington**

**Akira Ishimaru**

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APPROVED:

*Koichi Mano*

KOICHI MANO  
Project Engineer

APPROVED:

*Allan C. Schell*

ALLAN C. SCHELL, Chief  
Electromagnetic Sciences Division

FOR THE COMMANDER:

*John P. Huss*

JOHN P. HUSS  
Acting Chief, Plans Office

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→ The emphasis is directed towards generating new ideas and techniques to solve practical problems. Success in our effort is evidenced by the list of reports and publication. ←

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## EVALUATION

1. This is the Final Report on the contract which over the period from 1 December 1976 to 15 March 1980 investigated the radiometric determination of rain attenuation at millimeter wavelengths, atmospheric limitation on the wideband millimeter communication, backscattering from atmospheric irregularities, and diffusion of pulses in scatterers. The emphasis was placed on generating new techniques for solving practical problems.
2. The above work is of value since it enables one to form a quantitative understanding of the atmospheric effect and limitation on millimeter wave propagation pertinent to the design and operation of the Air Force communications and detection systems.

*Koichi Mano*

KOICHI MANO  
Project Engineer

## I Introduction

In recent years, numerous studies have been reported on the effects of various particulate matter and turbulence in the troposphere on millimeter wave propagation. In general, the problem of wave propagation in turbulence has been well studied in terms of the forward scatter approximation: This case is characterized by the extremely small refractive index fluctuations (the variance is of the order of  $10^{-12}$ ) and the turbulent eddy sizes which are much greater than a wavelength. In contrast with the turbulence case, many practical situations present very different problems. For example, in the wave propagation in fog, clouds, or snow, the refractive index of water is very much different from air and the particle sizes are comparable to or smaller than a wavelength. Unfortunately, there is a definite lack of understanding of the wave propagation and multiple scattering in the medium containing particulate matter and other inhomogeneities characterized by the particle sizes comparable to or smaller than a wavelength, particularly when the particulate matter is densely distributed. In practice, this is the situation often encountered for millimeter and optical waves in fog, clouds, rain, hail, and snow. Also microwave scattering from rough terrain surface and the volume scattering from terrain present the similar difficulties that the inhomogeneities are often of the order of a wavelength and are closely packed.

During the last few years, we have been concentrating our efforts on these areas as indicated above, which have not been clarified yet. We have developed a diffusion theory which may be applicable to dense random media. However the range of validity of this approximation has not been established yet. At present, therefore we have not obtained

complete formulas for angular (field-of-view) broadening, pulse broadening, amplitude and phase fluctuations, temporal and spatial spectra, polarization effects, the effects of beam waves, the effects of size distributions and the densities when millimeter waves are incident on various media including the particulate matter in the atmosphere and snow, vegetation and other random media in the terrain. We hope to continue to develop some fundamental formulations for these problems and to obtain useful numerical predictions for the wave propagation and scattering in these media.

## II Radiometric Determination of Rain Attenuation of Millimeter Wavelength

In rain attenuation measurement using a radiometer, scattering is usually negligible compared with absorption under 30 GHz and light rain. At millimeter wavelength, however, it is necessary to include multiple scattering effects. We have conducted a study of the effects of scattering taking into account the polarization effect and the drop size distribution.

The formulation is based on the equation of transfer with Stokes parameters. We assumed that rain is located in a plane-parallel region and that the thermal radiation from rain droplets obeys the Kirchhoff law. The absorption and scattering cross sections and the phase functions are calculated using the Mie solution and taking into account the Laws and Parsons size distribution. The index of refraction of water is calculated by using the formula given by Saxton.

For a plane-parallel problem, the specific intensities are functions of height and angle only. Letting  $I_v$  and  $I_h$  be the vertical and horizontal (parallel) components of the specific intensity, the equation of transfer becomes

$$\mu \frac{d}{d\tau} \bar{I} = -\bar{I} + \frac{1}{\sigma_t k^2} \int \bar{A} \bar{I} d\omega' + \text{source}$$

where  $\mu = \cos\theta$ ,  $\theta$  is the angle with the z axis,

$$\bar{I} = \begin{bmatrix} I_\ell \\ I_r \end{bmatrix}, \quad \bar{A} = \begin{bmatrix} |A_{11}|^2 & |A_{12}|^2 \\ |A_{21}|^2 & |A_{22}|^2 \end{bmatrix}$$

$A_{11}$ ,  $A_{12}$ ,  $A_{21}$ ,  $A_{22}$  are given by Z. Zekera. The general solution is a sum of a particular solution and a complementary solution. The complementary solution can be obtained by the eigenvalue technique.

The general boundary condition at ground is given by

$$T(\hat{s}) = [1 - \int R(\hat{s}, \hat{i}) \mu_i d\Omega_i] T_g + \int R(\hat{s}, \hat{i}) T(\hat{i}) \mu_i d\Omega_i$$

where  $\hat{s}$  and  $\hat{i}$  are unit vectors in the directions of scattering and incidence, and the integrals are taken over the upper hemisphere. If the diffuse scattering is uniform, then  $R(\hat{s}, \hat{i})$  is constant and is equal to (Albedo)/ $\pi$ , yielding

$$T(\hat{s}) = [1 - R_g] T_g + 2R_g \int_0^1 T(\hat{i}) \mu_i d\mu_i$$

where  $R_g$  is the albedo of the surface.

The general equation of transfer was solved using the eigenvalue technique. Calculations are made for the frequency ranges from 30GHz to 120GHz and various precipitation rates. For example, at 30GHz, for the rain temperature of 273°K, the precipitation rate of 12.5mm/hr, the ground temperature of 283°K, and the rain layer thickness of 2km, the calculated temperature for vertical and horizontal components are found to range from 171°K to 260°K and 171°K to 257°K respectively as the observed direction

varies from vertical to horizontal. But at 120GHz, the observed temperatures for vertical and horizontal polarizations vary from 248°K to 266°K and 248°K to 263°K respectively. Based on these calculations, the differences between the true rain attenuation and the attenuation calculated from the temperature measurements and the assumed rain temperatures can be calculated.

The computer calculations are made from 30 GHz, 60 GHz, and 120 GHz and the rain layer thicknesses of 1 km, 2 km, and 3 km. The albedo of ground is also varied, but the effect seems to be small. The precipitation rates used include 0.25 mm/hr, 12.5 mm/hr, and 100 mm/hr.

With the radiometric measurement technique, the attenuation by rain is usually estimated by the apparent attenuation

$$A_{\ell,r}(\text{db}) = 10 \log \frac{T_m}{T_m - T_{\ell,r}} \quad (1)$$

where  $T_m$  is the rain temperature and  $T_{\ell,r}$  are the vertical and horizontal brightness temperatures, respectively. This approximation is only true for frequencies below 30 GHz. At frequencies above 30 GHz and heavier precipitations, Eq. (1) is no longer valid because the scattering effects become comparable with absorption. The true attenuation should be calculated in the following way:

$$A_t(\text{db}) = (10 \log e) \frac{\rho \sigma t_0 z_0}{\cos \theta} \quad (2)$$

where  $z_0$  is the thickness of the rain layer and  $\theta$  is the observation angle. The true attenuation  $A_t$  is found to be greater than the apparent attenuations ( $A_\ell$ ,  $A_r$ ) and their differences have been calculated. For a small precipitation of 0.25 mm/hr, the differences between  $A_t$  and  $A_\ell$ ,  $A_r$  are under 3 db for frequencies below 120 GHz and Eq. (1) gives a good approximation.

The differences increase as the frequency and precipitation increase because more scattering occurs with higher frequencies and heavier precipitations.

It is also useful to plot the true attenuation ( $A_t$ ) vs. the vertical apparent attenuation ( $A_g$ ) so that the true attenuation can be conveniently found from the known vertical apparent attenuation. We compared our results with Zavody's theoretical study and Chadha-Lane's experimental data. Complete descriptions of our studies are included in the M.S. thesis by R. Cheung. A paper summarizing this study has been published. Our study and Zavody's are both based on spherical rain droplets. Chadha-Lane's experiment, however, showed noticeable differences between horizontal and vertical polarizations, indicating the effect of non-spherical rain droplets.

### III Atmospheric Limitation on Wide Band Communication

We have conducted a study of transmission characteristics of millimeter and optical waves under various atmospheric conditions. We have concentrated our attention to the atmospheric turbulence, rain and fog. We can summarize the general characteristics as follows:

#### (a) Millimeter Wave

Turbulence: The scale sizes of the turbulence are so much greater than a wavelength, and the angular spread of the wave is very small. Also the absorption is much smaller than the scattering. Therefore, the forward scatter theory is applicable in almost all ranges of practical interest and the theory is well developed.

Rain: The droplet sizes are comparable to a wavelength and the scattering cross section is of the same order as the absorption cross section. We have conducted extensive studies on this problem. We have examined the

range of validity of the first order multiple scattering solution in terms of the precipitation rate and the propagation distance. Above 10 GHz, the multiple scattering due to rain may become significant depending upon the precipitation rate, the thickness of the rain layer, and the observation angle. We considered the problem of a wave normally incident upon a plane-parallel rain region. The scattered wave is observed on the ground as a function of the elevation angle and polarizations, and it is calculated for 10, 30 and 120 GHz at the precipitation rate of 12.5 mm/hr with the rain layer thicknesses of 1 km and 3 km. The scattering characteristics of raindrops are calculated using the Mie solution and the Laws-Parsons distribution. Both the first order multiple scattering theory and the radiative transfer theory are used and the results are compared. It is shown that at 10 GHz, these two methods yield almost identical results. However at 30 GHz and 120 GHz, the first order scattering is smaller than that obtained from the radiative transfer theory, indicating the effects of higher-order scattering. It is also shown that the horizontal polarization is in general greater than the vertical polarization due to the scattering characteristics of raindrops. As the angle from the zenith increases, the scattering in vertical polarization decreases at 10 and 30 GHz. However at 120 GHz, the scattering in both polarizations decreases with the angle, indicating the effect of forward scattering. Based on the above study, the incoherent (fluctuating) intensity for a receiver with a given field of view or the receiving angle can be calculated. For example, with the receiver beamwidth of  $5^\circ$  and the rain thickness of 3 km, the incoherent intensity is approximately 50 db down from the coherent intensity at 10 GHz, but it is 20 db down at 120 GHz. The incoherent intensity for the rain thickness of 1 km is about 5 db less

than that for the rain thickness of 3 km.

Fog: The fog particle sizes are of the order of several microns and the Rayleigh scattering is applicable. The first order multiple scattering theory should be applicable in this case.

(b) Optical Wave

Turbulence: The scale sizes are much greater than a wavelength and the scattering is much greater than the absorption. The well developed forward scatter theory is applicable.

Rain: The droplet sizes are still greater than a wavelength and the scattering is greater than the absorption. The forward scatter theory should be applicable here.

Fog: The particle sizes are comparable to a wavelength and the scattering is much greater than the absorption. In this case, the diffusion should be predominant. We have conducted extensive studies on the transmission characteristics. We compared the exact solution with the diffusion solution to determine the range of validity of the diffusion theory.

(c) Coherence bandwidth of scattering medium

The coherence bandwidth of the atmospheric turbulence and hydrometeors is an important parameter in communication. We have made an extensive study on two-frequency mutual coherence function and pulse characteristics in fog, cloud, and turbulence. For particles, whose sizes are large compared with a wavelength, we obtained the coherence bandwidth  $\omega_{coh}$  as follows:

$$\omega_{coh} \sim \frac{10\alpha_p c}{z} \quad \text{when } \rho_n \alpha_s z < 1$$

$$\sim \left[ \frac{3}{\rho_n \alpha_s z} \right]^{1/2} \frac{2\alpha_p c}{z} \quad \text{when } \rho_n \alpha_s z \sim 1$$

$$= \frac{8\alpha_p z}{\rho_n \sigma_s z^2} \quad \text{when } \rho_n \sigma_s z \gg 1$$

where  $\rho_n$  is the number density,  $\sigma_s$  is the scattering cross section, and the scattering amplitude  $f$  is approximated by

$$|f|^2 = \frac{\alpha_p}{\pi} \sigma_s \exp(-\alpha_p s^2)$$

The pulse shape for a delta function input for  $\rho_n \sigma_s z \gg 1$  is given by

$$G(t) = \left[ \frac{\pi \omega_{\text{coh}}}{4} \right] \sum_{n=0}^{\infty} (2n+1)(-1)^n \exp\{-[(2n+1)\frac{\pi}{4}]^{\frac{1}{2}} T\}$$

where  $T = \omega_{\text{coh}}(t - \frac{z}{c})$ .

For turbulence, we obtained the coherence bandwidth:

$$\omega_{\text{coh}} = \frac{0.31 \omega_0}{\sigma_\chi^{12/5}}$$

where  $\omega_0$  is the carrier frequency and  $\sigma_\chi^2$  is the log-amplitude variance for the Rytov solution. We also obtained a universal pulse shape in the strong fluctuation region.

#### (d) Forward Scatter Theory and Diffusion Theory

The scale sizes of atmospheric turbulence are usually so large compared with a wavelength that the angular broadening is small and the forward-scatter theory is applicable. For waves in scatterers such as clouds and fog, the particle sizes are comparable to a wavelength and the diffusion phenomena become dominant at relatively short optical distances. It is therefore necessary to examine the two distinct states of propagation and scattering in random media: forward scatter and diffusion. In forward scatter region backscattering is negligible compared with forward scattering while there is as much backscattering as forward scattering in diffusion region. The

forward scatter theory is based on parabolic approximation where the scattering is confined in a small forward angular region. In contrast, the diffusion theory is based on an approximation where the angular spectrum is almost uniform. They are two asymptotic theories which can be derived from a general radiative transfer equation. Some formulations and approximation solutions in these two regions for both cw and pulse cases have been obtained. For a line-of-sight problem, the diffusion solution is seen to be applicable for optical scattering distance of greater than one. The transmitted flux, the angular spectrum and the pulse broadening are obtained. For backscattering, the diffusion solution is still applicable except for a short initial time. This is to be expected as the diffusion theory is not applicable near the boundary. The relationships between the forward scatter theory and the diffusion theory are not completely clarified yet and their range of validity should be established.

#### IV Effects of Transmitter and Receiver Characteristics on the Wave Fluctuation.

We have made extensive study on the effects of transmitter and receiver characteristics on amplitude and phase fluctuations in the weak fluctuation region. The variances of amplitude  $\langle \chi^2 \rangle$  and phase  $\langle S^2 \rangle$  fluctuation, including transmitter and receiver characteristics, are given by

$$\langle \chi^2 \rangle = \frac{\rho \sigma_s L}{2} \int_0^1 d\eta \left( \frac{1}{Q_1} - \operatorname{Re} \frac{1}{Q_2} \right)$$

$$\langle S^2 \rangle = \frac{\rho \sigma_s L}{2} \int_0^1 d\eta \left( \frac{1}{Q_1} + \operatorname{Re} \frac{1}{Q_2} \right)$$

where

$$Q_1 = \frac{\alpha_t}{\alpha_p} (1 - \eta)^2 + \frac{\alpha_r}{\alpha_p} \eta^2 + 1 + \frac{\rho \sigma_t L}{\alpha_p} \frac{(1 - \eta)\eta}{2}$$

$$Q_2 = \frac{\alpha_t}{\alpha_p} (1-\eta)^2 + 1 + \frac{\rho \sigma_t L - i 2 k L}{\alpha_p} \frac{(1-\eta)\eta}{2}$$

where

$$\alpha_t = \frac{2.77}{\theta_{tb}^2}, \quad \alpha_r = \frac{2.77}{\theta_{rb}^2}, \quad \alpha_p = \frac{2.77}{\theta_{pb}^2}$$

and  $\theta_{tb}$ ,  $\theta_{rb}$  and  $\theta_{pb}$  are the half-power beamwidths of the transmitter, receiver and scatterer, respectively. We have calculated both  $\langle \chi^2 \rangle$  and  $\langle S^2 \rangle$  for a rain medium with precipitations of 12.5 mm/hr and 50 mm/hr at 30, 60, 90 and 120 GHz and at optical frequency  $\lambda = 0.6 \mu$ .

At microwave frequencies (30, 60, 90 and 120 GHz),  $\langle \chi^2 \rangle$  and  $\langle S^2 \rangle$  are very close to each other. They both increase with the distance until they saturate at large distance. They also increase with the increase of frequency and precipitation. At optical frequency ( $\lambda = 0.6 \mu$ ,  $p = 12.5$  mm/hr), the difference between  $\langle \chi^2 \rangle$  and  $\langle S^2 \rangle$  can be significant.

These studies are made using the Gaussian model for the scattering pattern. However, further studies are needed using more realistic scattering patterns. It is also necessary to extend the results to the strong fluctuation region.

## V Backscattering of a Pulse

We have conducted a study of backscattered pulse in two asymptotic cases: forward scatter and diffusion.

The cumulative forward-scatter single-backscatter (CFSB) approximation were discussed by deWolf (IEEE Trans., AP-19, 254-262, 1971) and this is applied to a plane wave incident upon a slab for calculation of the backscattered two-frequency mutual coherence function, from which the backscattered pulse shape is found by Fourier transformation. The response to a general pulse may then be obtained by convolution. To employ this

technique, the forward-propagating two-frequency mutual coherence function is expressed as the solution to a parabolic equation. Multiple scattering effects are included, under the restrictions of small angular-spread of the wave and a narrow-bandwidth envelope for the incident pulse. The governing parameters for the pulse shape are the depth of the medium measured by the optical distance  $\tau$ , the albedo  $W_0$  and a parameter which is inversely related to the angular width of the averaged scattering pattern of the medium. When the scattering pattern is a Gaussian function, the latter parameter is  $\gamma = \ell^2 k_0^2 / 4$ , where  $\ell$  is the scale length of the correlation function of refractive index fluctuation and  $k_0$  is the wave number. The range of validity of the CFSB approximation is found to be approximately  $\tau \leq (2\theta_0/3)^2 \gamma / W_0$  where  $\theta_0$  is the allowable angular-spread within the medium. Although the overall temporal pulse width is always approximately  $2L/c$ , where  $L$  is the actual depth of the slab and  $c$  is the velocity of propagation, the pulse shape is best preserved when the time scale is normalized to  $2L/c\tau$ . The effect of non-unity albedo is to hasten attenuation. The effect of  $\gamma$  is surprisingly weak, as drastic increases in  $\gamma$  serve only to sharpen the leading and trailing edges of the overall pulse shape. Thus, asymptotic solutions may be valuable, and a closed-form solutions as  $\gamma \rightarrow \infty$  is presented. When scattering is instead characterized by a Kolmogorov process, the characteristic parameter  $k_0 L_0$  is introduced, where  $L_0$  is the outer scale length. The resulting pulse shape differs greatly from the pulse shape for a Gaussian spectrum. In this case the range of validity for the CFSB approximation is found to be  $\tau \leq (k_0 L_0)^{5/3} \theta_0^{5/3} / 12W_0$ . The effect of changing  $k_0 L_0$  is quite pronounced; however a closed-form asymptotic solution for the pulse shape as  $k_0 L_0 \rightarrow \infty$  is found, which in extreme conditions of short wavelength of a large outer scale size may be

a good approximation to actual behavior.

Diffusion of a short pulse in a dense scattering random medium has previously been studied using the time-dependent equation of transfer and its diffusion approximation (A. Ishimaru, JOSA, 68, 1045-1050, 1978). We studied a diffusion solution for a beam wave incident upon a slab of a dense scattering medium. The backscattered pulse shapes are calculated from the theory and compared with the experimental data. The experimental system was constructed by modifying the laser range-gating system (A. P. Bruckner, Appl. Opt., 17, 3177-3183, 1978). Using high power laser pulses ( $\sim 500 \text{ MW/cm}^2$ ) and an ultrafast shutter ( $\text{CS}_2$  between two crossed polarizers), we were able to record backscattered pulse shapes in a picosecond range. A beam of pulses with the pulse width of approximately 10 picoseconds at  $\lambda = 0.53 \text{ } \mu\text{m}$  is incident upon an aqueous solution containing latex microspheres. The latex spheres have diameters ranging from 0.5 to  $50 \text{ } \mu\text{m}$  and their concentrations are in the range of 0.1 to 30% in weight. The backscattered pulse shapes are digitized and stored for statistical processing. The pulse broadening for a 10% solution is a few picoseconds, while the broadening for a 1% solution is approximately 5 to 10 picoseconds. The pulse broadening increases as the concentration is decreased and for a 0.1% solution, the pulse broadening extends to several tens of picoseconds. The general pulse shape is characterized by a sharp rise time and slow tail. When the scatterers are absorbing, the tail part tends to suffer attenuation. The diffusion solutions are calculated using parameters obtained from the Mie solution and the known concentration. It is demonstrated that the theoretical predictions and the experiments agree well not only in the pulse shape and the broadening, but in the relative magnitudes of the pulse height for different particle sizes and concentrations as well.

# VI Diffusion of a Beam Wave in a Scattering Medium

The diffusion solution of a collimated beam wave normally incident upon a plane parallel layer of scatterers have been examined making use of the diffusion equation and boundary conditions given in Chapter 9 of Ishimaru's "Wave Propagation and Scattering in Random Media" - Vol. 1. By applying Green's function technique and using the Hankel transform, the solution for the Average Diffused Intensity  $U_d$  has been found:

$$U_d(r,z) = \int_0^\infty \frac{\lambda d\lambda}{\gamma} J_0(\lambda r) \frac{W_0^2}{2} e^{-\frac{W_0^2}{4} \lambda^2} \left\{ \frac{C_0}{2} A(z) + \frac{C_1}{4\pi h} B(z) \right\},$$

where  $\gamma = (\lambda^2 + K_d^2)^{1/2}$ ,  $W_0$  is the beam size of the incident collimated wave with Gaussian profile, and  $A(z)$  and  $B(z)$  are known functions of  $z$ .

The beam spread  $W_p$  is defined as:

$$\pi W_p^2 = \frac{2\pi \int_0^\infty F_z(r,d) r dr}{F_z(0,d)}$$

where  $F_z$  is the normal component of the transmitted flux at the exit end of the layer.

For example, at  $\lambda = 5\mu m$ , albedo  $\omega_0 = 0.8758$ ,  $\bar{\mu} = 0.7774$ ,  $W_0 = 1$  cm, the quantity  $(\frac{W_p}{W_0})$  increases to  $10^3$  when the optical thickness  $\tau$  of the layer is 10, and becomes  $7.0 \times 10^5$  when  $\tau = 20$ . We intend to continue to study the transmitted and reflected flux of the layer and the diffused flux distribution  $F_{dz}(r,d)$  at the end of the layer. The results for the small optical thickness are compared with the forward scattering results.

VII Personnel

Dr. Akira Ishimaru

Principal Investigator

Research Assistant

Completion Date

S. Hong

Post Doctoral

R. Cheung

(M.S. May 1978)

K. Painter

(M.S. November 1978)

K. Shimizu

(Ph.D. June 1979)

Y. Kuga

Ph.D.

VIII Journal Publications and Book

1. S. T. Hong, I. Sreenivasiah, and A. Ishimaru, "Plane wave pulse propagation through random media," IEEE Trans. on Antennas and Propagation, 25:6, pp. 822-828, November 1977.
2. A. Ishimaru, "The beam wave case and remote sensing," in Laser Beam Propagation Through the Atmosphere, Topics in Applied Physics, Strohbehn, editor. New York: Springer-Verlag, 1978
3. A. Ishimaru, "Theory and application of wave propagation and scattering in random media" (invited paper), Proc. of the IEEE, 65:7, pp. 1030-1061, July 1977.
4. A. Ishimaru, Wave Propagation and Scattering in Random Media, Volume I (Single scattering and transport theory) and Volume II (Multiple scattering, turbulence, rough surfaces, and remote sensing). New York: Academic Press, 1978.
5. A. Ishimaru, "Phase fluctuations in a turbulent medium," Applied Optics 16:12, pp. 3190-3192, December 1977.
6. A. Ishimaru, "Limitation on image resolution imposed by a random medium," Applied Optics, 17:3, pp. 348-352, March 1978.
7. R. Woo, F.-C Yang, and A. Ishimaru, "Probing the solar wind with radio measurements of the second moment field," Astrophysical Journal, 218:2, Part 2, pp. 556, December 1977.
8. A. Ishimaru, "Diffusion of a pulse in densely distributed scatterers," Jour. of the Optical Society of America, 68:8, pp. 1045-1050, August 1978.
9. A. Ishimaru, "Pulse propagation, scattering and diffusion in scatterers and turbulence," Radio Science (Bremmer Special Issue), 14:2, pp. 269-276, March-April 1979.
10. I. Sreenivasiah and A. Ishimaru, "Beam wave two-frequency mutual-coherence function and pulse propagation in random media: an analytic solution," Applied Optics, 18:10, pp. 1613-1618, May 1979.
11. A. Ishimaru and R. Cheung, "Multiple scattering effects on radiometric determination of rain attenuation at millimeter wavelengths," Radio Science, Vol. 15, No. 3, pp. 507-516, May-June 1980.
12. A. Ishimaru and K. J. Painter, "Backscattered pulse shape due to small-angle multiple scattering in random media," Radio Science, Vol. 15, No. 1, 1487-1497, Jan-Feb 1980.
13. K. Shimizu, A. Ishimaru, L. Reynolds, and A. P. Bruckner, "Backscattering of a picosecond pulse from densely distributed scatterers," Applied Optics, 18:20, pp. 3484-3488, October 1979.

14. K. Shimizu and A. Ishimaru, "Experimental test of the reduced effective velocity of light in a diffuse medium," *Optics Letters*, Vol. 5, No. 5, pp. 205-207, May 1980.
15. R. Woo, A. Ishimaru, and F.-Y. Yang, "Radio scintillations during occultations by turbulent planetary atmospheres," *Radio Science*, Vol. 15, No. 3, pp. 695-704, May-June 1980.

IX Paper Presentations and Meeting Attendances, 1 December 1976 to Present.

1. A. Ishimaru, "Effects on ray-bending on wave fluctuations," URSI Symposium on Electromagnetic Wave Theory, June 1977, Palo Alto.
2. A. Ishimaru, "Optical pulse propagation through turbulence, rain and fog," OSA Optical Meeting on Optical Propagation Through Turbulence, Rain and Fog, August 1977, Boulder.
3. A. Ishimaru, "Diffusion of a short pulse in randomly distributed scatterers," OSA Meeting, October 1977, Toronto.
4. A. Ishimaru, "Pulse diffusion in a dense distribution of scatterers," National Radio Science Meeting, January 1978, Boulder.
5. A. Ishimaru and R. Cheung, "Radiometric determination of rain attenuation at millimeter wavelengths," National Radio Science Meeting, January 1978, Boulder.
6. A. Ishimaru, "Theory of multiple scattering effects on optical pulse propagation in clouds" (invited paper), Naval Electronics Systems Command, March 1978, San Diego.
7. A. Ishimaru, "Wave fluctuations in rain and turbulence including transmitter and receiver characteristics," URSI Meeting, May 1978, Silver Spring, Maryland.
8. I. Sreenivasiah and A. Ishimaru, "Backscattered pulse from turbulence and scatterers," URSI Meeting, May 1978, Silver Spring, Maryland.
9. A. Ishimaru, "Optical pulse propagation in fog and clouds," NSF Meeting on Optical Communications, June 1978, Pittsburgh.
10. A. Ishimaru, "Propagation, diffusion and scattering of a pulse in a random medium," 1978, Sendai, Japan.
11. A. Ishimaru, "Optical scattering and diffusion in turbulence and scatterers," OSA Meeting, October 1978, San Francisco.
12. K. Shimizu and A. Ishimaru, "Estimation of size distribution of randomly distributed scatterers," OSA Meeting, October 1978, San Francisco.

13. A. Ishimaru, "Forward scatter and diffusion of pulses in a random distribution of scatterers," URSI Meeting, November 1978, Boulder.
14. A. Ishimaru, "Multiple scattering effects on pulse propagation through fog and clouds," Naval Ocean Systems Center Program Review, November 1978, San Diego.
15. A. Ishimaru and R. Woo, "Interpretation of radar measurements of the sun," AFU Meeting, December 1978, San Francisco
16. A. Ishimaru, "Forward scatter theory and diffusion theory for wave in random media," Bremmer Session, National Radio Science Meeting, June 1979, Seattle
17. A. Ishimaru, "Multiple scattering effects on backscattering of a pulse from terrain," National Radio Science Meeting, June 1979, Seattle.
18. K. J. Painter and A. Ishimaru, "Backscattered pulse shape due to small-angle multiple scattering from a slab of random medium," National Radio Science Meeting, June 1979, Seattle.
19. K. Shimizu, A. Ishimaru, and A. P. Bruckner, "Backscattering of a picosecond pulse from a dense scattering medium," National Radio Science Meeting, June 1979, Seattle.
20. R. L.-T. Cheung and A. Ishimaru, "Multiple scattering of millimeter waves in rain," National Radio Science Meeting, June 1979, Seattle.
21. S. Yano, A. Ishimaru, and J. Yee, "Input impedance of a circular microstrip disk antenna: analytical study and comparison with experiment," IEEE Antennas and Propagation Symposium, June 1979, Seattle.
22. K. Shimizu, A. Ishimaru, and L. Reynolds, "Diffusion and scattering of a picosecond pulse in a dense scattering medium," OSA Meeting, October 1979, Rochester.
23. A. Ishimaru and R. L.-T. Cheung, "Multiple scattering effects on wave propagation due to rain," URSI Commission F Symposium, Lennoxville, Canada, May 1980.

X Other Activities Related to this Contract.

1. A. Ishimaru was appointed a Distinguished National Lecturer of IEEE AP-S for 1976-1977. His topic was "Wave Propagation and Scattering in Random Media" and the lectures were given at the University of Michigan and Ohio State University in January 1976, McGill University in March 1977, and Stanford University in April 1977.
2. A. Ishimaru was an invited distinguished lecturer at the University of California, Irvine, March 1977.

3. A. Ishimaru was invited to participate in a Navy Advisory Panel, May 1977.
4. A. Ishimaru was invited to present a paper, "Theory of multiple scattering effects on optical pulse propagation in clouds," and chaired a session at the Blue-Green Cloud Propagation Workshop of the Naval Electronics System command, San Diego, March 1978.
5. A. Ishimaru was invited to participate in the Basic Engineering Research Scoping Workshop for the U.S. Department of Energy, Washington, D.C., May 1978.
6. A. Ishimaru presented an invited paper and chaired a session at the 1978 International Symposium on Antennas and Propagation, Sendai, Japan, August 1978.
7. A. Ishimaru was appointed an Official Representative to the 19th General Assembly of the URSI, Helsinki, Finland, July/August 1978, representing the National Academy of Sciences and National Research Council of the United States.
8. A. Ishimaru was appointed editor of RADIO SCIENCE for four years beginning January 1979.
9. A. Ishimaru was invited to participate in the workshop on "Theoretical and Experimental Analysis of Radar Backscatter from Terrain," January 9-11, 1979, Fort Belvoir, Virginia, sponsored by the University of Kansas, the Army Research Office, the Naval Research Lab, and the Army Engineer Topographic Laboratories.
10. A. Ishimaru served as Technical Program Chairman for the IEEE International Symposium on Antennas and Propagation and the National Radio Science Meeting held at the University of Washington, Seattle, June 18-22, 1979.
11. A. Ishimaru was invited to speak at the Symposium on Recent Developments in Classical Wave Scattering held at Ohio State University, June 25-27, 1979.
12. A. Ishimaru was invited to speak at the Chemical Systems Laboratory Scientific Conference on Obscuration and Aerosol Research, U.S. Army, Aberdeen Proving Ground, Maryland, September 1979.
13. A. Ishimaru was invited to speak on "Theoretical and experimental study of transient phenomena in random media" at the workshop on "Wave Propagation in Turbulent Media," sponsored by the Mathematics Division, U.S. Army Research Office, March 24-26, 1980, at Virginia Polytechnic Institute, Virginia.



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